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Shanidar 3 Neandertal rib puncture wound and paleolithic weaponry

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ABSTRACT

Since its discovery and initial description in the 1960s, the penetrating lesion to the left ninth rib of the Shanidar 3 Neandertal has been a focus for discussion about interpersonal violence and weapon technology in the Middle Paleolithic. Recent experimental studies using lithic points on animal targets suggest that aspects of weapon system dynamics can be inferred from the form of the bony lesions they produce. Thus, to better understand the circumstances surrounding the traumatic injury suffered by Shanidar 3, we conducted controlled stabbing experiments with replicas of Mousterian and Levallois points directed against the thoraces of pig carcasses. Stabs were conducted under both high and low kinetic energy conditions, in an effort to replicate the usual impact forces associated with thrusting spear vs. long-range projectile weapon systems, respectively.

Analysis of the lesions produced in the pig ribs, along with examination of goat ribs subjected primarily to high kinetic energy stabs from an independent experiment, revealed consistent differences in damage patterns between the two conditions. In the case of Shanidar 3, the lack of major involvement of more than one rib, the lack of fracturing of the affected and adjacent ribs, and the lack of bony defects associated with the lesion (such as wastage, hinging, and radiating fracture lines) suggests that the weapon that wounded him was carrying relatively low kinetic energy.

While accidental injury or attack with a thrusting spear or knife cannot absolutely be ruled out, the position, angulation, and morphology of the lesion is most consistent with injury by a low-mass, low-kinetic energy projectile weapon. Given the potential temporal overlap of Shanidar 3 with early modern humans in western Asia, and the possibility that the latter were armed with projectile weapon systems, this case carries more than simple paleoforensic interest.

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Introduction

Excavation at Shanidar Cave, in the Zagros Mountains of northeastern Iraq, resulted in the discovery of nine Neandertal skeletons between 1953 and 1960 (Solecki, 1963; Stewart, 1977; Trinkaus, 1983), making Shanidar the richest Neandertal site yet discovered in western Asia. One adult male from the site, Shanidar 3, has a very well-preserved thoracic skeleton (Trinkaus, 1982, 1983; Ogilvie et al., 1998; Franciscus and Churchill, 2002), which exhibits a partially healed injury to the left 9th rib. This antemortem lesion, originally described by Stewart (1969, 1977) and Trinkaus (1983; Trinkaus and Zimmerman, 1982), appears to represent sharp force trauma from a lithic point or blade, and has led to guarded speculation concerning interpersonal violence among the Shanidar Neandertals (Solecki, 1960; Stewart, 1969, 1977; Trinkaus and Zimmerman, 1982; Trinkaus, 1983; Shea, 1990; Holdaway, 1990; Solecki, 1992), or possibly interspecific violence between Neandertals and early modern humans (Roper, 1969).

Shanidar 3 is thus one of two Neandertals bearing evidence of antemortem traumatic injury from a lithic implement (the other being the ca. 36,000 year old, Châtelperronian-associated adult male from St. Césaire, France [Zollikofer et al., 2002]). A third specimen, an adult male, Mousterian-associated, early modern human from Skhul Cave, Israel, may also bear a weapon-inflicted perimortem wound (McCown and Keith, 1939), although this case is much more equivocal (see below). The evidentiary value of isolated cases such as these is limited, as any number of equally possible yet untestable scenarios concerning the manner of death

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of these individuals (including intragroup, intergroup, or interspecific violence, hunting accident, or other type of accident) can be proposed (Walker, 2001; Zollikofer et al., 2002), and their analyses may seem like little more than exercises in paleoforensic conjecture.

Nonetheless, identifying the nature of the weapon that injured Shanidar 3 and discerning the circumstances surrounding his death are important beyond simple forensic interest. If indeed Shanidar 3 was the victim of interpersonal violence, then this case contributes to our understanding of the nature of internecine or intergroup conflict among Pleistocene hunters and gatherers (Gat, 1999; Walker, 2001; Shea, 2003a) and the role of weapon technology in the evolution of human social behavior (such as coalitionary behavior [Bingham, 1999, 2000; Shea, 2006]).

Perhaps more importantly, this case (and that of St. Césaire) may be related to the issue of competitive interaction among closely related species of the genus *Homo*. Neandertals (*Homo neanderthalensis*) and early modern humans (*H. sapiens*) both occur in the fossil record of western Asia during the interval between 130–40 ka. However, modern human remains have been recovered from sites dated between 130–80 ka, after which they seem to disappear from the record until around 50 ka, roughly coincident with the appearance of Upper Paleolithic assemblages in the Levant (Bar-Yosef et al., 1996; Mellars, 2006), suggesting two separate colonization events (Shea, 2003a,b). Neandertal fossils appear in archeological levels as old as 120 ka, but are most abundant in levels spanning the interval between 80–50 ka, before disappearing from the record between about 50–45 ka (Valladas et al., 1999; Holliday, 2000). Shanidar 3 derives from layer D1 (Solecki and Solecki, 1993), near the top of the Mousterian sequence at Shanidar and slightly below two radiocarbon samples that produced (uncalibrated) dates of 46.9 ± 1.5 ka and 50.6 ± 3.0 ka (Vogel and Waterbolk, 1963). The re-incursion of modern humans into western Asia is not reflected in the human fossil record of northern Iraq, and is thus impossible to pinpoint chronologically, although a juvenile modern human skeleton from Ksar Akil in Lebanon suggests that modern humans had reached western Asia prior to 40 ka (Bergman and Stringer, 1989; Mellars and Tixier, 1989). The timing of the first appearance of the early Upper Paleolithic Baradostian, or "Zagros Aurignacian" (Olszewski and Dibble, 1994, 2006), which may signal the arrival of modern humans, is also poorly resolved. The oldest radiocarbon date derived from the Baradostian assemblage in layer C of Shanidar is 35.4 ± 0.6 ka (Olszewski and Dibble, 1994, 2006), which is consistent with uncalibrated radiocarbon dates recently obtained for this industry from Yafteh Cave, about 350 km to the southeast: the oldest of which, that is near but not at the bottom of the Aurignacian level, is 35.5 ± 0.6 ka (Otte et al., 2007). However, the claim that the Zagros Aurignacian (Baradostian) developed *in situ* from the local Mousterian (Otte and Kozlowski, 2007) suggests that the modern humans who recolonized western Asia during OIS 3 may have been associated with Middle Paleolithic toolkits, and thus may have been present well before the first Upper Paleolithic assemblages were deposited in the area. The ^{14}C dates from layer D at Shanidar were obtained in the early 1960s using the solid carbon method, and their reliability is questionable (Olszewski and Dibble, 2006): thus, while Shanidar 3 may predate the second coming of modern humans in western Asia (some suggest the specimen may be as old as 75 ka [Trinkaus, 1983]), it is also possible that he lived at a time of Neandertal/modern human sympatry. St. Césaire, on the other hand, most certainly did (Lévêque and Vandermeersch, 1980; Vandermeersch, 1984; Mercier et al., 1991).

Thus, both of these cases may pertain to the issue of interspecific interaction and competitive exclusion (Gat, 1999; Walker, 2001; Shea, 2003a, 2005; O'Connell, 2006). The penetrating lesion in the rib cage of Shanidar 3 becomes of even greater interest given recent suggestions that true long-range projectile weapons (in the form of spearthrower and dart) may have been a component of the modern human tool kit – but not that of the Neandertals – after 50 ka (McBrearty and Brooks, 2000; Brooks et al., 2005; Shea, 2003b, 2006; Rhodes and Churchill, 2009; Churchill and Rhodes, 2009). Projectile weapons may have given modern humans an edge that allowed them to out-compete and replace indigenous populations of archaic humans (such as the Neandertals) as they spread out of Africa (O'Connell, 2006), and may have been a component of direct antagonistic interactions between hominin species (Shea, 2003a,b).

While most discussion of the evolution of projectile weaponry has focused on its role in hunting, its function in various forms of violent conflict in hunter-gatherers – from social coercion to coalitionary killings to warfare - has not been overlooked (Bingham, 1999, 2000; Shea, 2003a, 2006; O'Connell, 2006). While aggressive encounters between comparably armed groups of hunters and gatherers would entail great risk of injury and death to both sides (see references in Shea, 2003a), a disparity in technology involving weapons capable of killing at a distance may have tipped the balance in favor of preemptive coalitionary attacks under some circumstances. As noted by Shea (2003a:184), "we cannot rule out more direct, confrontational competition. Upper Paleolithic humans were not fools, nor were they necessarily nice people. If they perceived Neandertals as ecological rivals and had the ability to displace them by coalitional killing, they probably did so." Projectile weapons were certainly a component of violent social interactions in the Upper Paleolithic/Later Stone Age (Wendorf, 1968; Wendorf and Schild, 1986; Bachechi et al., 1997; Bocquentin and Bar-Yosef, 2004), just as they have been among more recent hunters-gatherers (see references in Keeley, 1996; Gat, 1999; Walker, 2001; Thorpe, 2003; Smith et al., 2007): they may well, then, have been a part of the way that early modern humans interacted with Neandertals.

In this light, forensic-type analysis of the costal lesion in Shanidar 3 takes on new significance. Recent experimental work on bone lesions caused by hafted lithic points (Karger et al., 1998; Lombard et al., 2004; Parsons and Badenhorst, 2004; Smith et al., 2007) suggests that important attributes of prehistoric weapon systems (such as mode of delivery and amount of kinetic energy imparted to the target) can be inferred from lesion morphology and trace evidence remaining in the bone. We report here on lesions produced in goat and pig ribs under controlled stabbing experiments intended to simulate the impact dynamics of hand-delivered and spearthrower-thrown spears tipped with Middle Paleolithic stone points, and revisit the case of Shanidar 3 in light of these findings.

The Shanidar 3 skeleton, the lesion, and its traumatic sequelae

The Shanidar 3 partial skeleton was excavated as an isolated burial by R.S. Solecki during the 1957 and 1960 field seasons at Shanidar Cave. The vertebrae and ribs of Shanidar 3 were found in more or less anatomical position (Figs. 1 and 2), although some disturbance of other postcranial elements, most likely from rockfalls within the limestone cave, was apparent. According to Solecki (1960), the individual was lying between large rocks, on his right side, and with his legs flexed close to his trunk. As with the other individuals from the Shanidar sample, it is not clear whether Shanidar 3 was intentionally buried, or instead killed and buried within the cave by a rock fall (Tillier et al., 1988; Solecki, 1989; but see also Gargett, 1989, and comments therein). Trinkaus (1983, 1991), however, argued from a variety of lines of evidence that intentional burial for Shanidar 3 (along with Shanidar 1, 4, 6, and 7) was more likely.

Figure 1. *In situ* view of Shanidar 3 after its initial discovery in the 1957 excavation season. Articulated lumbar vertebrae (right arrow) and scattered ribs (left arrow) are evident (Photograph courtesy R.S. Solecki).

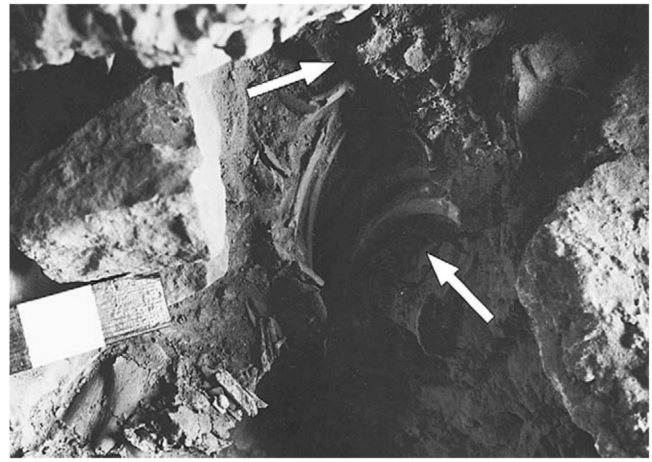

Figure 2. *In situ* view of Shanidar 3 during the 1960 excavation season. Thoracic vertebrae (left arrow) and several ribs (right arrow) can be seen in approximate anatomical position amid large stones in the east wall of the excavation. (Photograph courtesy R.S. Solecki).

The skeleton of Shanidar 3 is considered that of a male based on the robusticity and shape of the ischiopubic ramus, ischial spine, absence of scarification of the preauricular surface, and morphometric analyses of humeral and talar length, humeral distal articular breadth, and radial head diameter (Trinkaus, 1983). Estimation of age at death using dental wear, pubic symphyseal and sacroiliac morphology, and the presence of degenerative joint disease results in a range of 40–50 years (Trinkaus, 1983), and histomorphometric analyses of cortical bone have narrowed this range to estimates of 41 and 42 years (Thompson and Trinkaus, 1981; Trinkaus and Thompson, 1987; Abbott et al., 1996). Shanidar 3 thus represents one of the oldest (age at death) known Neandertals (see Trinkaus, 1995). In addition to a traumatic injury to the thorax, Shanidar 3 suffered from severe degenerative joint disease in the talocrural and talocalcaneal articulations in the right foot (Trinkaus and Zimmerman, 1982; Trinkaus, 1982, 1983). The asymmetrical nature of the osteoarthritis (the preserved elements of the left foot evince no degenerative joint disease) suggests that it might have developed secondary to a traumatic injury to the right foot or leg.

The costal lesion consists of a parallel-sided groove on the left 9th rib (L9), located about 60 mm ventral to the posterior angle. The lesion traverses the cranial aspect of the shaft to a depth of ca. 3 mm (Fig. 3). The groove is 9.7 mm in length along its floor and is oriented from lateral-ventral to medial-dorsal, and at an angle of 79° to the plane of the external surface of the rib. The groove descends slightly from the lateral aspect to the medial aspect and is marked by exostoses along its margins, especially dorsal to the groove. The area of exostotic remodeling along the cranial margin of the rib extends 12.2 mm dorsoventrally and 8.8 mm mediolaterally. Radiographs (Fig. 4) indicate somewhat increased cortical density around the wound.

The groove is parallel-sided, more so in its lateral (external) aspect than in its medial (internal) aspect (Fig. 5). The groove widens internally, such that the maximum width of the lateral (external) aspect is only 1.5 mm, while the more irregular medial (internal) opening is 2.6 mm in maximum width. Microscopic examination indicates no evidence for exostoses within the wound itself, and the parallel-sided walls of the lateral aspect consist of irregular woven bone. It is also apparent under magnification that the bottom (inferior) floor of the groove is neither V-shaped nor flat but rather gently rounded.

The suprajacent left 8th rib exhibits a modest bone irregularity along the crest of the costal groove on its caudal margin, precisely in line with the 9th rib groove when properly aligned (Fig. 5). The irregularity is ca. 6 mm in length, and based on microscopic analysis is clearly not due to postmortem damage. This small exostotic irregularity likely represents a periosteal reaction to nicking of the inferior margin of the rib by the implement that created the lesion in the rib below (or incidental contact with the implement that might have remained lodged in the wound [see below] as the two ribs approximated one another during exhalation).

The parallel-sided walls of the wound and the lack of an exostotic reaction within the lesion itself led Stewart (1969, 1977) to surmise that the blade of the weapon had broken off and remained in place in the rib (such that reactive bone growth developed around the foreign object), and was still in place at the time of death (cf. Trinkaus, 1983). To Stewart, failure to recover a corresponding blade of stone or bone suggested that the point had been made of wood and had subsequently decayed. Solecki (1992), on the other hand, saw the morphology of the lesion as being consistent with injury from a thin stone point (cf. Shea, 1990), and Trinkaus (1983) suggested the tip of the armature was lost postmortem (displaced when the rib fractured below the groove after death, and not recovered in the excavation of the burial). Examples of fragmentation of flint weapon armatures, with detached pieces remaining embedded in human bone, are known both historically (Bill, 1862; Coues, 1866; Wilson, 1901) and archaeologically (see Smith et al., 2007). A non-human example from the western Asian Mousterian comes from the site of Umm el Tlel in Syria (Boëda et al., 1999), where a fragment of a Levallois point was found embedded in the cervical vertebra of an equid.

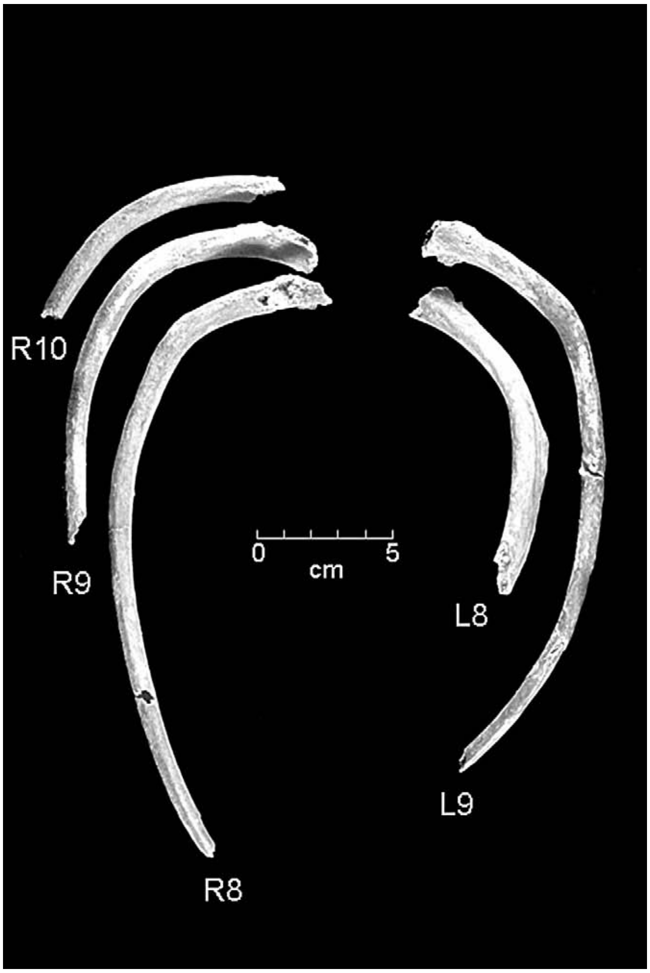

Figure 3. Superior view of vertebrochondrial ribs. Note grooved puncture wound on L9.

Figure 4. Radiographs of a) superior, and b) medial views of the left 9th rib showing the angle and extent of the healed puncture wound (arrows).

The morphology and position of the lesion has led to the suggestion that the tip of the armature possibly punctured the pleura of the left lung, resulting in a pneumothorax (Stewart, 1969, 1977; Trinkaus, 1983). The position of the lesion on L9 would be adjacent to lung tissue on inhalation and to the wall of the diaphragm on exhalation, and at a minimum the penetrating wound would have incised the parietal and diaphragmatic pleura of the left thoracic cavity. Assuming the injury resulted in a simple pneumothorax (as opposed to a tension pneumothorax, hemothorax, or hemopneumothorax) of relatively small size (i.e., the amount of air admitted into the pleural space was $<$20% of the volume of the pleural space, and did not entirely collapse the lung), the chances of post-traumatic survival without medical intervention are fairly good (see Johnson, 1996; Weissberg and Refaely, 2000). Of 473 patients admitted to an urban hospital with thoracic stab wounds, slightly more than a third (37%) suffered only a pneumothorax, and 5% experienced no ruptures to the pleura (Madiba et al., 2001). Of the total pool of patients, approximately 27% were treated non-operatively, and thus represent cases where survival without medical intervention would have been likely (providing an estimate of the odds of Shanidar 3 surviving a penetrating chest wound). While some patients with hemo- or hemopneumothorax did not require surgical intervention (or drainage), their proportions were lower than those with simple pneumothorax only (17% vs. 35% [Madiba et al., 2001]). Based on these data, if the stab wound to Shanidar 3 either did not puncture the pleura or created only a simple pneumothorax, his odds of survival without medical intervention would likely have been better than 35%. Post-traumatic complications, such as infection, tend to occur with low frequency in modern stabbing cases (Khammash and El Rabee, 2006), and in the case of Shanidar 3 no evidence of infection is present.

That Shanidar 3 survived the traumatic insult for a period of at least two weeks is evidenced by the bony callus formation seen around the lesion. The time necessary for healing responses to skeletal trauma varies by individual, by skeletal element, and by the nature of the traumatic damage. Still, osseous responses sufficient to alter the gross morphology of an injured bone generally take several weeks to first appear (Lovell, 1997; Walker et al., 1997; Sauer, 1998). Ragsdale et al. (1981) claimed that it takes 10 days to three weeks after a bone injury before sufficient mineralization has occurred that a periosteal reaction is visible radiographically. Studies of casualties of the American Civil War, for whom both date of injury and date of death are known, show that osteoblastic responses (periosteal reactions) to cranial trauma were entirely absent in soldiers who died within the first week after injury, and present in only 43% of those who died in the second week (Barbian and Sledzik, 2008). The same skeletal series also shows that, in cases of comminuted fractures of the long bones, *initial* callus formation may not be evident until six to nine weeks post-trauma (Tichnell, 2008). Thus, Shanidar 3 survived at least two weeks, and probably several weeks longer. However, the composition of the callus (woven bone) indicates a lack of a coordinated osteoclastic/osteoblastic response (i.e., true remodeling), suggesting death within about two months of receiving the injury (see Walker et al., 1997; Barbian and Sledzik, 2008). The ultimate cause of death of Shanidar 3 is unknown: he may have succumbed to infection

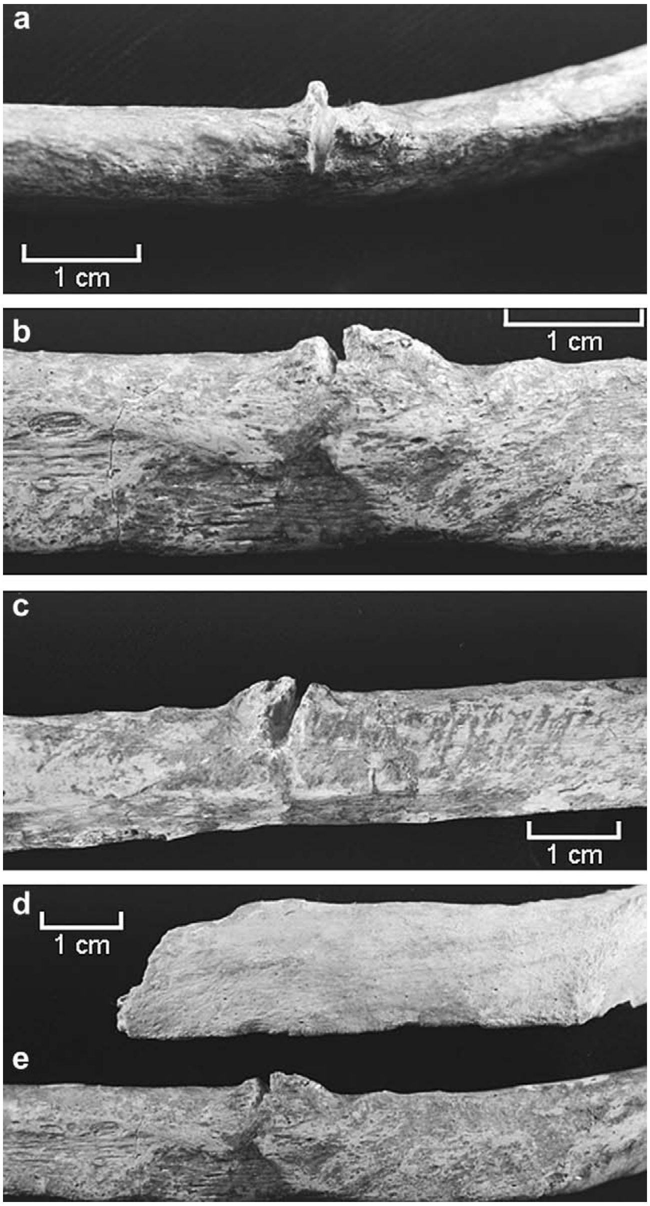

Figure 5. a) Superior oblique view of wounded L9 showing parallel-sided entry of groove and interior of groove; b) lateral (external) view showing parallel-sided configuration of groove; c) medial (internal) view showing less parallel-sided configuration of groove; d) lateral (external) view of L8 aligned in anatomical position with e) L9. Note the slight remodeling and involvement of inferior aspect of L8 in the injury.

secondary to the thoracic trauma, died as a consequence of other injuries that were sustained at the same time but are not evident in the preserved skeletal elements, or died from factors unrelated to the thoracic trauma (such as a roof collapse in the cave [Solecki, 1989; Solecki and Solecki, 1993]).

Experimental approaches to lithic sharp force trauma

Projectile and hand-delivered weapon systems vary in dynamic properties such as velocity (v), kinetic energy (KE), and momentum (p). Variation within and across types of primitive weapon systems, along with variation in the attributes of their armatures (such as tip cross-sectional area and cutting angle), lead to variation in weapon penetration depth, tissue damage, and lethality. Hand-delivered spears and true long-range projectile weapons (spearthrower darts and arrows) generally differ considerably in the mass of the weapon and its impact velocity, and therefore in the kinetic energy and momentum imparted to the target. While there is a long-standing idea that transfer of momentum[1] is the principle agent of tissue damage in wound ballistics (Hatcher, 1935), experimental studies and theoretical considerations show that the transfer of kinetic energy[2] is the primary determinant of wound severity (Mendelson, 1991) and that the role of momentum is negligible (Sellier and Kneubuehl, 1994; Karger and Kneubuehl, 1996). We thus sought to conduct stabbing experiments at kinetic energies characteristic of hand-thrust spears and spearthrower-propelled darts to see how the skeletal lesions they produced (in ribs of a similar size to those of Shanidar 3) might differ, and to determine what if anything might be inferred from the morphology of the lesion about the dynamic properties of the weapon that produced it.

For spearthrower-propelled darts (hereafter simply referred to as "darts"), characteristic values of KE and p can be determined from mass and velocity data derived from experimental studies using replicas of ethnographically- or archaeologically-known spearthrowers and darts (or in some cases the actual weapons themselves) (see Hughes, 1998). These studies suggest a range of KE values between about 8 J to 51 J, with a central tendency of about 26–28 J (Table 1). Because the darts tend to be fairly light (about a tenth of a kilogram, on average) and the launch velocities relatively low (better than throwing a spear by hand, but generally only a third- to a half-that of arrows fired by primitive bows [see Hughes, 1998: Table 1]), darts tend to impart very low momentum to their targets (generally less than 4 kg m sec^{-1}).

Determining the kinetic energy and momentum of thrusting spears is more difficult, since an unknown amount of the hunter's body (arm and upper trunk) contributes to the mass of the weapon system. Therefore, we used force and velocity data from a simulated spear thrusting experiment (Schmitt et al., 2003) in which subjects were asked to stab a target as if they were trying to penetrate an animal with a thrusting spear to determine KE and p (experimental work by Lombard et al. (2004) showed that living prehistorians so instructed can generate the forces necessary to penetrate the thoracic cavity of large herbivores). In this study, subjects thrusted an instrumented aluminum pole into a padded target. The output of strain gauges implanted on the pole, calibrated by pushing the pole against a force plate, allowed Schmitt et al. (2003) to determine impact forces at contact with the target. Spear velocities were determined from time-synched lateral video recordings, and the period of deceleration (i.e., impact time) was determined by the interval between initiation and cessation of the strain gauge signal (see Schmitt et al. (2003) for details).

Schmitt et al. (2003) reported an average force at impact of 1660 N and an average spear velocity of 1.7 m sec^{-1} in the

[1] Momentum (p) is the product of the mass (M, in kg) and velocity (v, in m sec^{-1}) of an object, and is thus expressed in units of kg m sec^{-1}. Thus, a heavy (1 kg) Mousterian spear thrown by hand at 15 m sec^{-1} would have a momentum of 15 kg m sec^{-1}, while a light (0.1 kg) dart propelled by a spearthrower at 23 m sec^{-1} would have a momentum of 2.3 kg m sec^{-1}. Despite its higher velocity, the low mass of the dart results in momentum an order of magnitude lower than that of the spear. If momentum were the principle factor in wound severity, we would expect the hand spear to penetrate farther and do more damage than the dart.

[2] Kinetic energy (KE) is proportional to mass times velocity squared, and is calculated as 0.5 $M\,v^2$ (and is thus expressed in units of kg m^2 sec^{-2}, or Joules [J]). Thus, a heavy (1 kg) Mousterian spear thrown by hand at 15 m sec^{-1} would have a KE of 112.5 J, while a light (0.1 kg) dart propelled by a spearthrower at 23 m sec^{-1} would have a KE of 26.5 J. Under the idea that KE is the principle factor in wound severity, we would still expect the hand spear to penetrate farther and do more damage than the dart.

Table 1
Velocity (v), mass, kinetic energy (KE), and momentum (p) of spearthrower darts as determined from replicative experiments.

Study	v (m sec^{-1})	Mass (g)	KE (J)	p (kg m sec^{-1})
Hill (1948)	26.9	21.3	7.7	0.6
Hill (1948)	25.7	28.4	9.4	0.7
Hill (1948)	24.8	85.1	26.2	2.1
Mau (1963)	24.5	71.0	21.3	1.7
Howard (1974)	24.0	166.0	47.8	4.0
Spencer (1974)	24.8	63.0	19.4	1.6
van Buren (1974)	21.2	185.5	41.7	3.9
van Buren (1974)	20.3	155.0	31.9	3.1
van Buren (1974)	19.5	182.0	34.6	3.5
Raymond (1986)	21.0	70.0	15.4	1.5
Bergman et al. (1988)	23.0	193.0	51.0	4.4
Mean ± SD (Median)	23.2 ± 2.4 (24.0)	110.9 ± 65.9 (85.1)	27.9 ± 14.9 (26.2)	2.5 ± 1.4 (2.1)

Velocity and mass data for all studies as reported in Hughes (1998).

experiments, and the deceleration of the spear occurred over 0.03 seconds (Schmitt et al., 2003: Fig. 2). Given the average force and deceleration (1.7/0.03 sec), the "effective" mass of the spear (that is, the mass of the spear plus the moving portions of the thruster) can be determined to be 29.2 kg. This equates with a KE = 42.2 J and p = 49.6 kg m sec^{-1}, and thus kinetic energy that falls at the upper end of the range for darts, but far more momentum. Note that peak force and velocity values reported by Schmitt et al. (2003) reached 3430 N and 4.5 m sec^{-1}. Given impact times of 0.01–0.02 seconds, the mass component of the system operating at maximum force can be estimated at 7.6–15.2 kg. Thus, it seems that at higher impact forces the thruster is getting less of his/her body into the stab, and is instead accelerating the spear more as a projectile (albeit one that never leaves the hand). Maximum KE with spear thrusting is thus on the order of 77.0–153.9 J, and p ranges from 34.2–68.4 kg m sec^{-1}. Therefore, the estimates of KE for the thrusting spear are higher than those obtained for darts, but overlap the upper end of the range of reported values, whereas the estimates of the momentum for the thrusting spear are uniformly higher (by an order of magnitude) than observed for darts (Table 2).

We examined the ribs of two goats that had participated (postmortem) in a stabbing experiment with stone-tipped spears (Shea et al., 2001). The ribcages of these goats had been repeatedly penetrated with a thrusting spear, tipped with replica Levallois points of various sizes, and propelled by a calibrated crossbow at speeds of 1.0–1.5 m sec^{-1} and KE of 28–63 J. The ribcages of these goats were kindly provided to us by John Shea, and were cleaned of soft tissue by dermestid beetles. The damage to the ribs was extensive, and in the case of one of the goats the damage was so extensive and had resulted in so many detached and unidentifiable fragments that analysis of the remains was not possible. The precise number of blows suffered by each goat is not known (the purpose of the study involved understanding the damage incurred to the lithic points, not to the goats) but was likely in the dozens. From the perspective of understanding the relationship between rib injuries and the dynamic properties of prehistoric weapon systems, the ribs of these goats presented two additional problems. First, the amount of energy delivered by each stab was variable and at times consistent with spearthrower darts, and at other times with more forceful thrusting spear use. The nature of the experimental design left us no means by which to relate variation in the traumatic damage to the ribs to variation in the dynamics of the stabs. Second, goat ribs are gracile relative to those of humans (and especially relative to the large, robust ribs of Neandertals [see Table 3]), and may fracture at lower KE values, or otherwise respond differently to the forces associated with a penetrating wound, than would those of larger, human ribs.

For these reasons, we repeated the stabbing experiment under conditions in which we could better differentiate the effects of low versus high KE stabs, and on ribs (those of pigs) that more closely approximated the robusticity of those of Shanidar 3. The ribs of the pigs used in this study were more similar in midshaft dimensions to those of Shanidar 3 than were the goat ribs from the study by Shea et al. (2001) (Table 3). While the pig ribs were shorter (dorsoventrally) than those of Shanidar 3 (as measured by the tuberculoventral chord), their greater midshaft minimum diameters gave them a robusticity (as reflected in [midshaft maximum * minimum diameter]/tuberculoventral chord) more similar to that of Shanidar 3, and thus presumably more similar biomechanical properties as well. Pig skin is similar in thickness and mechanical response to that of human skin, and has been argued to be a good model for human skin in various clinical studies (Shergold et al., 2006). Measurement of backfat thickness in two meat industry Landrace pigs (that were roughly 25% and 53% larger than the pigs used in this study) produced values of 19.9–22.2 mm (Barowicz et al., 2006), which is likely to be some four to five times thicker than that of a well-fed Neandertal (given that hunter-gatherer males tend to range between 5% and 15% body fat [Eaton et al., 1988]). It is also likely that meat industry pigs and Neandertals differed in thickness of thoracic musculature. However, experimental work on puncture wounds reveals that the mechanical properties of skin and bone (which, as argued above, are similar in Neandertals and pigs) are the primary determinants of penetration, and that variation in fat and muscle thicknesses are of negligible importance (Ankersen et al., 1999). Thus, the pigs used in this study should stand as reasonable mechanical models of a Neandertal thorax.

To better understand the circumstances surrounding the traumatic injury suffered by Shanidar 3, we conducted controlled stabbing experiments with replicas of Mousterian and Levallois points directed against the thoraces of pig carcasses. Stabs were conducted under both high and low kinetic energy conditions, in an effort to replicate the usual impact forces associated with thrusting spear vs. long-range projectile weapon systems, respectively.

Table 2
Comparison of mean kinetic energy (KE) and momentum (p) for darts, thrusting spears, and spears used in this study.

	KE (J)	p (kg m sec^{-1})
Darts[a]	27.9 ± 14.9	2.5 ± 1.4
Thrusting spears[b]	42.4	49.6
Crossbow spear[c]	28–63	–
Crossbow spear[d]		
15 kg draw weight	16.0–16.2	4.1–4.2
31 kg draw weight	47.3–47.7	7.0–7.1

[a] Data from Table 1.
[b] Based on experimental work by Schmitt et al. (2003) (see text for details).
[c] As used by Shea et al. (2001) on the goat ribs examined in this study.
[d] As used in this study on pig ribs.

Table 3
Dimensions (mm) of the eighth rib of Shanidar 3, recent European Americans, and the goat and pigs used in this study.

	MMXD[b]	MMND[b]	TVC[b]	Robusticity[c]
Shanidar 3[a]	16.6	8.4	248.3	56.2
European Americans ($n = 19$)[a]	15.1 ± 2.0	6.3 ± 0.9	227.9 ± 16.1	41.7[d]
Goat 1	12.2	5.4	200.7	32.8
Pig 1	10.8	8.3	151.9	59.0
Pig 2	13.7	7.8	175.0	61.1

[a] data from Franciscus and Churchill (2002).
[b] MMXD: midshaft maximum diameter; MMND: midshaft minimum diameter; TVC: tuberculoventral chord. All measurements following Franciscus and Churchill (2002).
[c] Midshaft robusticity, calculated as 100*(MMXD*MMND)/TVC.
[d] Based on mean rib dimensions.

Materials and methods

We used a calibrated crossbow, modified from the design provided by Shea et al. (2001), to launch stone-tipped spears a short distance into pig carcasses. As with the apparatus used by Shea and coworkers, our crossbow employed tandem-mounted fiberglass bows (Glassflex® recurved youth bows, with draw weights of 13.5–16 kg each) and a plastic aiming tube. However, our crossbow used a draw-and-release system that allowed us to launch the spear, such that all of the stored strain energy in the bow staves had been imparted to the spear. Thus, unlike the apparatus used by Shea et al. (2001), which thrust but did not launch the spear, our crossbow launched the spear (over a distance of only 2–4 cm) such that the bow itself was not contributing to the energy and momentum at impact. The flight distance was sufficiently small that loss of velocity to air resistance can be assumed to be negligible.

The spears were tipped with one of three lithic points representative of points from the late Mousterian of western Asia: a Mousterian point, a Levallois point, and an elongated Levallois point. Mousterian points are a common occurrence in the Zagros Mousterian, including layer D at Shanidar (Solecki and Solecki, 1993), and, although Levallois points tend to be rare in the Zagros, they do occur with low frequency (see Baumler and Speth, 1993; Dibble and Holdaway, 1993). Because Mousterian points are a more common occurrence in the Zagros Mousterian, we conducted 50% of the stabbing trials with this point type. The points were replicas of Levantine Middle Paleolithic points, made by Dodi Ben-Ami (Katzrin, Israel) from flint collected on Mt. Carmel, Israel. Dimensions of the points are provided in Table 4. Each point was hafted to a wooden foreshaft with artificial sinew and Liquid Nails® adhesive. The spear itself was a 1.22 m-long bamboo shaft, nocked at one end to receive the bowstrings. The foreshafts were fitted into the distal end of the spear shaft, and a snug fit was ensured by wrapping the proximal ends of the foreshaft with 3M Scotch® duct tape.

The spear shaft had a mass of 411.1 g, and the foreshafts + points ranged in mass from 115.4–120.2 g. Thus, the total mass of the spear ranged between 526.5–531.2 g depending on which point was in use. The crossbow was positioned such that the spear had completely separated from the bowstrings before the point hit the target. Therefore, the spears were acting as simple projectiles (albeit projectiles that were flying distances of only 2–4 cm) and no stored energy in the bow staves was contributing to the force of the thrust. The draw weight of the crossbow was calibrated with a Chatillon® DFM50 digital force gauge at various draw lengths. The maximum draw weight provided by the two bows in tandem was 31 kg. Because spearthrower darts tend to carry relatively low KE and hand-thrust spears tend to carry greater KE, we conducted stabbing trials at two draw weights: 31 kg and 15 kg.

Through free-flight experiments,[3] we estimated the velocity of the spears to be 13.4 m sec^{-1} at the 31 kg draw weight and 7.8 m sec^{-1} at the 15 kg draw weight. Given these velocities, the high-energy stabs (at 31 kg draw weight) impacted the target with KE in the range of 47.3–47.7 J and momentum of about 7.0–7.1 kg m sec^{-1}. These KE values are close to the experimentally-determined mean value for thrusting spears (Table 2), although admittedly within the high end of the range of values reported for spearthrower darts. The momentum attained by our high-energy thrusts were considerably lower than those estimated for thrusting spears, but still two- to ten-times that usually delivered by darts. The low-energy stabs (15 kg draw weight) yielded a range of KE of 16.0–16.2 J and momentum range of 4.1–4.2 kg m sec^{-1}. Thus, the KE values for our low-energy stabs are low relative to the mean value observed for darts, but within the range of reported values. The momentum imparted by our low-energy stabs is consistent with that delivered by spearthrower-propelled darts (Table 2). In some cases the platform of the crossbow was inclined downwards by as much as 5° to facilitate aiming. Given the short distance traveled by the spear (<0.5 m), the short acceleration intervals (0.038–0.064 sec), and the small contribution that gravity would make to accelerating the spear at such a shallow launch angle (producing a total increase in launch velocity of 0.03–0.05 m sec^{-1}), inclining the platform did not substantially alter the KE values of the stabs.

Two dressed (that is, with internal organs and blood removed but still retaining skin, subcutaneous fat, and muscles) juvenile Landrace pigs were purchased from a commercial wholesaler in North Carolina. The pigs had dressed weights of 61.8 kg and 62.3 kg, corresponding to live weights of 84.1 kg and 84.5 kg, respectively. We did not measure skin, subcutaneous fat, and muscle thicknesses, all of which vary across the back and torso. However, as discussed above, we feel the pigs represent reasonable mechanical models for a Neandertal thorax.

The pigs were separated through the lumbar vertebrae, and their upper bodies (thorax, forearms, and head) were suspended against a tree with the dorsum of the pigs facing outwards. The first pig received six low-energy stabs to its left-side ribs and three high-energy stabs to its right-side ribs, all with the Mousterian point (on the third high-energy stab the hafting sinew was displaced proximally, rendering the point unusable). The second pig received five stabs to its right-side ribs with the elongated Levallois point (three low-energy stabs to the right caudal thoracic quadrant and two high-energy stabs to the right cranial quadrant) and four stabs with the Levallois point to its left-side ribs (two low-energy stabs to

Table 4
Dimensions of lithic points used in this experiment.

	Point type		
	Mousterian	Levallois	Elongated Levallois
Length[a]	92.3	77.1	108.9
Width[a]	40.9	46.7	42.7
Thickness[a]	14.5	14.7	8.8
TCSA[b]	297	343	188
Tip angle[c]	45°	58°	32°

[a] Maximum length, width, and thickness in mm.
[b] Tip cross-sectional area (mm^2), calculated as 0.5*width*thickness, following Shea (2006).
[c] Penetrating angle of tip (Friis-Hansen, 1990).

[3] Free-flight experiments were conducted by launching the spears on a flat trajectory (that is, with the launching platform horizontal) and measuring the horizontal distance (d) traveled by the tip of the spear before it struck the earth. Given that the launch platform was 1.1 m off the ground, the spears had a flight time (t) of 0.112 sec before striking the ground. Since $d = vt$, launch velocity (v) could then be determined from distance as $v = d/0.112$.

the left caudal quadrant and two high-energy stabs to the left cranial quadrant). The number of traumatic insults per pig and per side was kept small so as to limit the potential for damage from one blow obscuring damage from a previous blow. The location and depth of each penetrating wound was recorded. After the experiment, the head, upper limbs, and skin of the pigs were carefully resected, leaving the thoracic vertebrae, ribs, and thoracic muscular, which were macerated by boiling followed by hand-preparation (while exercising great care to avoid introducing cut marks to the ribs from the preparation tools).

All of the ribs (both goat and pig) were examined for lesions attributable to sharp force trauma (Sauer, 1984; Maples, 1986) and for perimortem fracturing (Lovell, 1997). The nature of the lesions produced by each stab (either V-shaped incisions of varying depth or puncture wounds) and associated features (see below) were recorded. Complete fractures (in which there was a complete break in the continuity of bone, resulting in ribs that were broken into two or more pieces) were differentiated from infractions (fracture lines longer than 5 mm that did not separate the rib into multiple pieces). The former generally consisted of transverse fracture lines (running craniocaudally) or, less often, oblique fracture lines; the latter more often consisted of oblique and longitudinal (running parallel to the long axis of the rib) fractures and in some cases involved significant displacement of the distal portion of the rib body (producing an angulation in the body of the rib).

Trauma from sharp instruments can produce lesions with a number of associated defects, including radiating fracture lines, hinging of pieces of cortical bone around the site of impact, wastage (detachment and loss of pieces of bone adjacent to the lesion), and crushing of adjacent bone tissue (Sauer, 1984; Maples, 1986; Spitz, 1992; Byers, 2007). Radiating fractures appear as small (usually <5 mm) fracture lines emanating from the lesion and generally running parallel to the long axis of the rib body (that is, following the "grain" of the cortical tissue), while hinging involves the partial detachment and displacement of chips of cortical bone adjacent to the lesion (representing sections of bone tissue that have been wedged away, but not separated from, the cortex by the force of the impacting projectile). A lesion was considered to exhibit wastage if moderate-to-large pieces (>5 mm diameter) of cortical bone were detached *adjacent* to the point of impact: displaced bone tissue from within the lesion itself (the cortical tissue that was removed by the projectile point in the formation of the characteristic V-shaped notch) was not considered wastage. In some cases wastage involved the loss of sizable (ca. 30 mm diameter) sections of cortical bone from the necks or bodies of ribs. Finally, a lesion was considered to exhibit crushing if small pieces of cortical bone were displaced inwardly (towards the medullary space), resulting in a depressed area without loss of cortical tissue.

Results

Pig ribs

In the experiment with pig carcasses, we delivered a total of seven stabs under high KE conditions. The first pig received three high-energy stabs to its right-side rib cage with the spear tipped with the Mousterian point. All three of these blows produced V-shaped incisions in two adjacent ribs (Table 5). At an average depth of 90 ± 3 mm, the points had clearly penetrated to a depth at which point width exceeded the diameter of the intercostal space, and thus both edges of the lithic forcefully contacted (and incised) the margins of the adjacent ribs. Five of the six affected ribs sustained complete fractures. The exception was rib R9, which evinces only a V-shaped lesion on its caudal margin, along with some hinging of small chips of bone and some crushing of the neighboring cortical bone. The adjacent 10th rib, however, suffered a complete fracture and evinces a large area of wastage on its internal surface (Fig. 6), as well as a V-shaped incision on its cranial margin.

The second pig received two high-energy stabs to the cranial portion of its right thorax with the elongated Levallois point. One of these stabs landed in the area of the costal cartilage and missed the ribs altogether (penetrating so deeply as to embed the point into

Table 5
Experimentally-induced trauma in pig ribs under high- and low- kinetic energy (KE) conditions.

Point Type[a]	Penetration Depth (mm)	Trauma
High KE		
M	87	V-shaped lesions to caudal margin of R9 and cranial margin of R10, complete fracture with wastage of R10, (pig 1) (Fig. 6).
M	89	V-shaped lesions to caudal margin of R11 and cranial margin of R12, complete fracture of both ribs, wastage in R11 (pig 1).
M	93	V-shaped lesions to caudal margin of R6 and cranial margin of R7, complete fracture of both ribs (pig 1).[b]
EL	92	V-shaped lesions to caudal margin of R6 and cranial margin of R7, complete fracture of R7 (pig 2) (Fig. 7).
EL	>92	None.[c]
L	71	V-shaped lesions to caudal margin of L7 and cranial margin of L8, complete fracture with wastage of both ribs (pig 2).
L	63	None.[d]
Low KE		
M	55	Small V-shaped lesion to caudal margin of L10 (pig 1) (Fig. 9).
M	31	Small V-shaped lesion to cranial margin of L14 (pig 1).
M	61	Infractions of L12 and L13 (no lesions, no displacement of distal rib) (pig 1).
M	6.9	Small V-shaped lesion to cranial margin of L8 (pig 1) (Fig. 8).
M	85	Puncture to distal dorsal surface of L9 (pig 1).
M	38	Small V-shaped lesion to caudal margin of L5 (pig 1).
EL	74	None.
EL	67	V-shaped lesion to cranial margin of R10, with complete fracture (pig 2)[d] (Fig. 10).
EL	65	Small V-shaped lesions to caudal margin of R13 and cranial margin of R14 (pig 2).
L	55	Small incision on caudal margin L12 (pig 2).
L	56	V-shaped lesions to caudal margin of L11 and cranial margin of L12, complete fracture with wastage of both ribs (pig 2).

[a] M = Mousterian Point; L = Levallois Point; EL = Elongated Levallois Point.
[b] Hafting material (sinew) displaced proximally.
[c] Point entered thorax beyond distal extent of ribs (in area of costal cartilage) and embedded in tree behind pig, snapping the point in half.
[d] slight damage to lithic tip (loss of ca. 1–2 mm of distal tip).

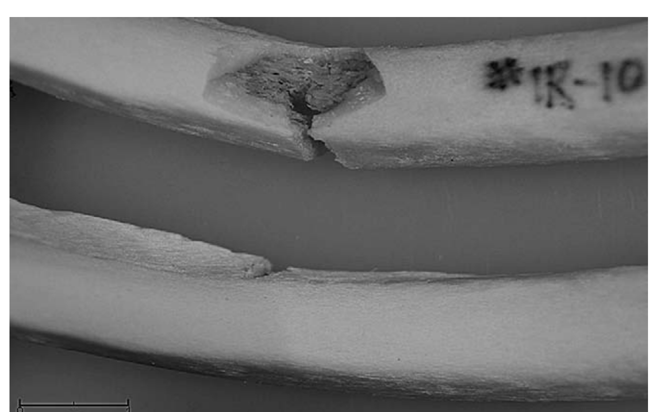

Figure 6. Pig 1 ribs R9 (bottom) and R10 (top) in ventral perspective, showing damage caused by a single high-energy stab with a Mousterian point. While R9 bears only a V-shaped lesion on its caudal margin, the subjacent R10 evinces complete fracturing and extensive wastage in addition to the primary lesion.

the tree behind the pig, transversely snapping off the distal half of the lithic). The other high-energy blow produced lesions in the 6th and 7th ribs, with a complete fracture of the 7th rib (Fig. 7). Rib R6 did not fracture, but sustained a lesion with wastage and hinging. This pig also received two high-energy stabs to the cranial portion of its left-side rib cage with the Levallois point. One of these stabs, oddly, produced no visible bone lesions yet did manage to transversely snap off the distal millimeter or so of the point tip (it is possible that the point entered the intercostal space sideways [passing between two ribs with the width of the point parallel and its thickness perpendicular to them], and the tip contacted the bark of the tree behind the pig). The other blow produced V-shaped lesions in the ribs L7 and L8, both of which also suffered complete fractures (Table 5).

A total of 11 low KE stabs were delivered to the two pigs (Table 5). The first pig incurred six low-energy stabs with the Mousterian point to its left-side ribs. All six of these stabs produced visible damage to the ribs: with one exception, however, the damage from each stab was confined to a single rib. Three of the low-energy stabs produced V-shaped incisions on the margin of a rib, with no associated wastage, hinging, crushing, or fracture lines (Fig. 8 and 9). One stab produced a very narrow incision with slight hinging and displacement of a strip of cortical bone, and another produced a puncture wound on the distal lateral surface of the 9th rib, with some slight crushing of bone around the margins of the lesion. Only one blow resulted in rib fracturing: a low-energy stab that struck between the 12th and 13th ribs produced infractions (without significant displacement) in both ribs, but did not produce lesions in either rib.

The caudal portion of the right-side rib cage of the second pig was subjected to three low-energy stabs with the elongated Levallois point (Table 5). One of these stabs left no discernable lesions. One low-energy stab produced a V-shaped lesion in the distal end of the 10th rib, with wastage of very small chips of bone (ca. 1 mm diameter) on the rib margin proximal and distal to the lesion. This stab also produced a complete, transverse fracture through the relatively narrow distal rib shaft (Fig. 10), as well as a transverse break to the distal 2 mm of the lithic tip. The other low-energy stab with this point produced a superficial V-shaped incision on the adjacent caudal and cranial margins of the right 13th and 14th ribs, respectively (with no associated defects).

Finally, the caudal portion of the left-side rib cage of the second pig received two low-energy stabs with the Levallois point (Table 5). One of these blows left only a small V-shaped incision on the caudal margin of the proximal 12th rib. The other blow produced more damage to the relatively gracile midshafts of the 11th and 12th ribs. This latter stab produced relatively deep V-shaped incisions in the adjacent margins of the two ribs, along with transverse, complete fractures of the shaft. The lesion in the 11th rib has an associated small radiating fracture line and slight hinging of a small chip of cortical bone. The internal surface of the 12th rib is missing a moderate-sized piece of cortical bone (wastage).

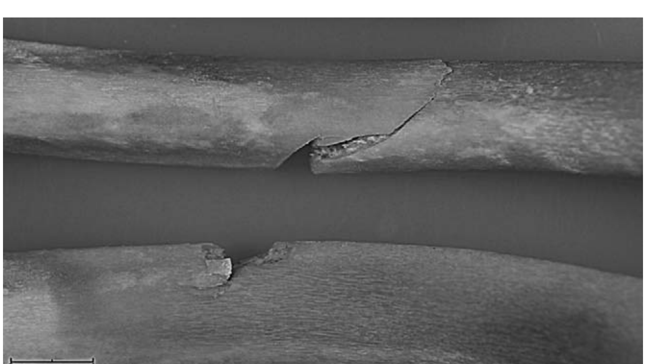

Figure 7. Ventral view of Pig 2 ribs R6 (bottom) and R7 (top), showing damage caused by a single high-energy stab with an elongated Levallois point. Note hinging of bone adjacent to lesion in R6 and complete fracture of R7.

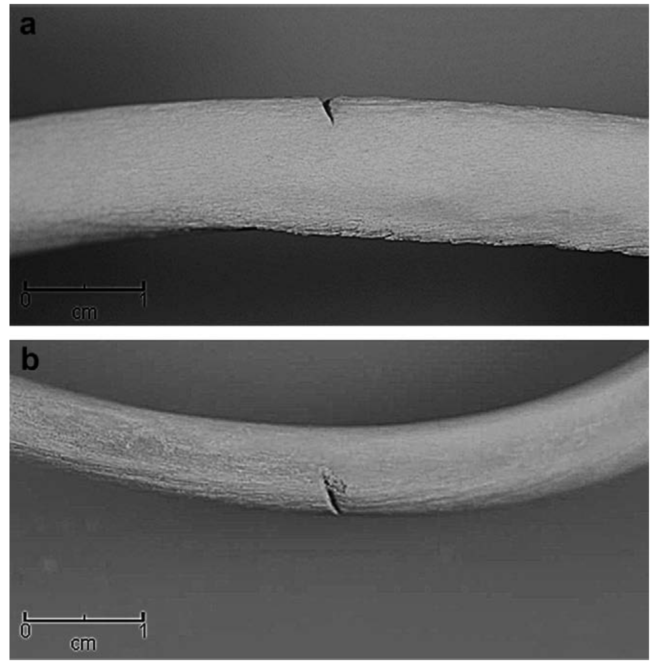

Figure 8. Pig 1 rib L8 in lateral (a) and cranial (b) views, showing lesion caused by low-energy stab with a Mousterian point. Note the lack of wastage, fracturing, and other sharp force traumatic defects.

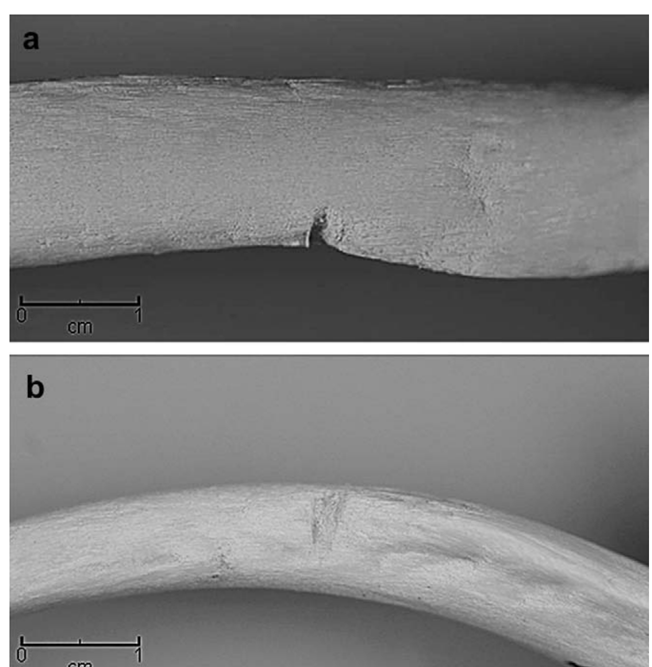

Figure 9. Pig 1 rib L10 in lateral (a) and caudal (b) views, showing lesion caused by low-energy stab with a Mousterian point. Note the lack of wastage, fracturing, and other sharp force traumatic defects.

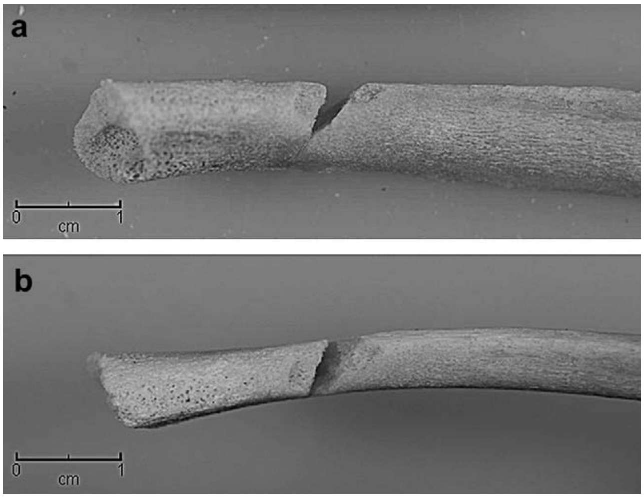

Figure 10. Pig 2 rib R10 in medial (a) and cranial (b) views, showing lesion produced by a low-energy stab with an elongated Levallois point. Although difficult to discern in the photograph, this rib did evince a complete fracture.

Although the performance of the lithic points was not the focus of this work, it does bear noting that the elongated Levallois point, with the smallest tip cross-sectional area and sharpest tip angle (Table 4), seems to have penetrated furthest under both low- and high-energy conditions (Table 6). The Mousterian point, with its more symmetrical shape, seems to have outperformed the more irregularly-shaped Levallois point on high KE thrusts, but the two points appear to have performed comparably on low KE thrusts. It is also interesting that at low kinetic energy, none of the points penetrated to a depth sufficient to cause contact between the elements of the haft (sinew, glue, and the distal portion of the foreshaft) and the tissues of the pig carcasses. This shallow penetration is no doubt a function of the relatively large tip cross-sectional areas of these points (see Shea, 2006), and illustrates the pressures that must have existed to reduce projectile armature size to increase the penetration of missiles carrying low KE and momentum (Hughes, 1998). With smaller armatures and greater penetration depths (as characteristic of Upper Paleolithic armatures [Shea, 2006]), points must incorporate design features (such as shoulders, stems, or notches) that reposition hafting materials away from the cutting surfaces of the point. It is also interesting to note, consistent with the experience of Lombard et al. (2004) in similar experiments, that one particular deep penetration (under the high KE condition) resulted in a loosening and proximal displacement of the binding material.

Goat ribs

Of the 26 goat ribs, 19 exhibited sharp force traumatic lesions or perimortem fracture, and several ribs bore multiple lesions. Nine ribs sustained one or more complete fractures, and another two had infractions (incomplete fractures) through the shaft sufficient to result in displacement of the distal rib body relative to the proximal portion. Two of these 19 ribs bore only superficial scratch marks, morphologically similar to cut marks from lithic butchery tools, on their cranial or caudal margins. Fifteen ribs appear to have been directly impacted by a lithic tip, although extensive wastage (loss of bone) around the site of impact in several cases obliterated the actual area of lithic/bone contact (in which case impact was inferred rather than observed). Of 16 identifiable lesions, 13 (81%) preserved lithic residue, observable at 10x magnification, embedded in the bone at the site of impact, including one lesion with a small lithic chip (ca. 1 mm $\times$ 0.5 mm) wedged into the trabeculae at the impact site (cf. Parsons and Badenhorst, 2004; Smith et al., 2007). Interestingly, none of the lesions in the pigs – from either high-energy or low-energy insults – contained lithic residue. This may reflect differences in the raw material properties of the points, although both studies (that of Shea et al. [2001] and this study) used replicas made by the same flintknapper, who presumably collected flint from a single source in Israel. A number of the lesions also contained hairs, although it is not clear if these were driven into the wound by force from the spear impact (that is, transferred from the hide to the bone lesion), or introduced incidentally during the maceration process.

A total of seven lesions (ca. 44%) were associated with complete fractures, two with infractions with displacement of the distal rib body, and two ribs sustained complete fractures despite having no observable lesions (these ribs were likely fractured from inward deflection of the abdominal musculature from a blow adjacent to the ribs). Excluding the two instances of superficial scratches, extensive wastage around the site of impact obliterated the actual sharp force lesion in most cases (Fig. 11). In only two cases were parallel-sided or V-shaped (as viewed in cross-section) lesions apparent (Fig. 12). One of these was associated with a complete fracture through the rib shaft and a small amount of wastage along the affected rib margin both proximal and distal of the area of impact. The other was a small lesion to the cranial margin of a rib body, in which hinging and slight displacement of a flake of cortical bone has produced the appearance of a parallel-sided lesion.

Table 6
Mean penetration depths (mm) of lithic points under high- and low- kinetic energy (KE) conditions (mean $\pm$ SD [n]).

	Point type			
	Mousterian	Levallois	Elongated Levallois	Total
High KE	90 ± 3 (3)	67 ± 6 (2)	$92 \pm (1)$[a]	83 ± 12 (6)
Low KE	57 ± 20 (6)	56 ± 1 (2)	67 ± 5 (3)	60 ± 15 (11)
Total	68 ± 23 (9)	61 ± 7 (4)	75 ± 12 (4)	

[a] one trial under this condition missed the ribs and produced a penetration of >92 mm in depth while embedding in the tree.

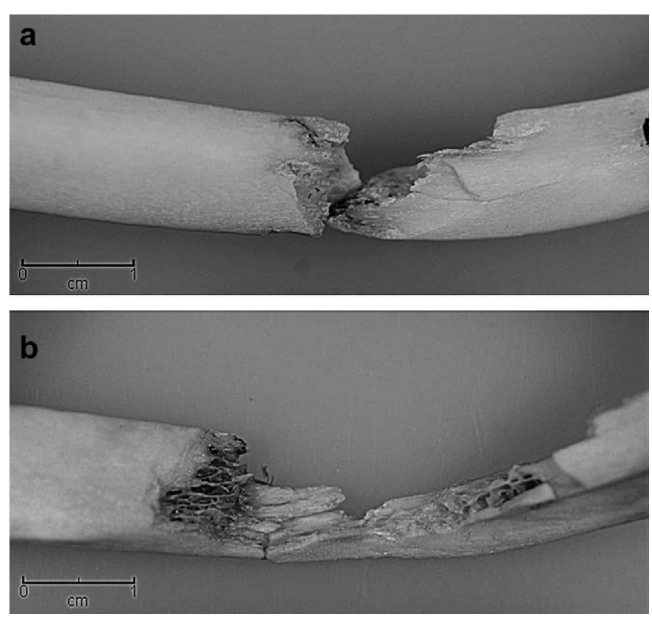

Figure 11. Goat ribs damaged by high KE stabs, illustrating extensive wastage (with obliteration of the actual impact area) and complete fractures characteristic of high energy impacts: a) rib L5 in dorsolateral view (note radiating fracture line emanating from proximal side of lesion); b) rib R6 in ventral view.

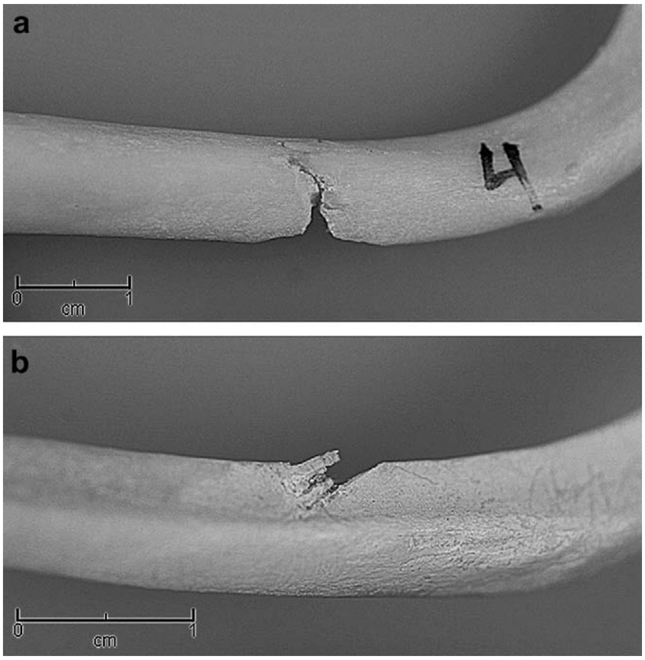

Figure 12. Goat ribs L4 (a: dorsal) and L9 (b: dorsal), representing the only cases in which the high KE stabs produced relatively deep incisions that were not obliterated by wastage (but note moderate wastage of cortical bone on the caudal margin of L4 just proximal and distal of lesion). Note the complete fracture of rib L4 and the hinging of bone adjacent to the lesion in L9.

The combined results of the pig and goat experiments reveal that the incidence of bone defects associated with the sharp force trauma differed markedly in ribs struck under high and low energy conditions (Table 7). High KE stabs appear to be much more likely to produce complete fractures of the ribs, to generate wastage, and to produce radiating fracture lines and hinging of bone pieces. Crushing also appears to be somewhat more common in cases of high KE stabs. Note that we have considered all of the lesions and traumatic damage observed in the goat ribs to have been produced by high KE stabs (Table 7), when in fact some of them may have resulted from thrusts with relatively low KE. Thus, it is possible that we have either underrepresented the frequency of defects that occur with low energy stabs (some of the defects attributed to high KE stabs were produced by low KE events), or underrepresented the frequency of defects associated with high KE stabs (by adding in to the sample low KE lesions without defects). In either case, the data from the pigs does not suffer from this problem, and suggests a clear difference in the degree to which these two conditions produce bone defects. What is particularly relevant is the finding that *all* of the defects produced under high KE conditions had at least one (and usually multiple) associated defects, whereas slightly more than half of the low KE lesions had *no* associated defects.

Table 7
Occurrence of defects associated with sharp force trauma in goat and pig ribs.

	Low KE	High KE		
	Pig	Pig	Goat[a]	Goat[a] + Pig
Number of lesions observed	11	10	16	26
Complete fractures[b]	25.0%	70.0%*	57.9%	62.1%
Radiating fracture lines	9.1%	50.0%*	56.3%	53.8%
Wastage	9.1%	80.0%*	68.8%	73.1%
Hinging	18.2%	50.0%*	81.3%	69.2%
Crushing	9.1%	10.0%	25.0%	19.2%
Lesions with no associated defects	54.5%	0.0%*	0.0%	0.0%

* = observed frequency significantly different ($p < 0.05$) from frequency expected based on damage observed in pig ribs stabbed under low KE conditions, based on one-way Chi-square test. Chi-square test conducted on pig results only.

[a] In constructing this table, we considered the lesions and traumatic damage seen in the goat ribs to have been produced by high KE stabs: some may have been produced under low KE conditions (see text for details).

[b] Including infractions with significant displacement of the distal corpus. Percentage calculated relative to the ribs that bear either lesions or fractures (12 in the low KE pigs, 10 in the high KE pigs, 19 in the goat).

Discussion

The nature of the damage seen in the goat and pig ribs strongly suggests that the penetrating wound to Shanidar 3 occurred under low kinetic energy conditions. A number of observations lead us to this conclusion. First, the injury to Shanidar 3 is *essentially* confined to one rib (with due recognition of the small periosteal reaction on the suprajacent rib). In the experiment with pigs, 71% of the high energy stabs penetrated so deeply that they created clear lesions on two adjacent ribs. In fact, the only cases in which we did not observe major involvement of two ribs were the two cases that produced no lesions whatsoever (one of these because the spear penetrated in the area of the costal cartilage). Conversely, under the low KE conditions most of the stabs produced lesions in only one rib (most likely due to the shallower penetration depths). Out of 11 low KE stabs, only three (27%) caused damage to two adjacent ribs (one of these cases involved infractions without evident lesions), while seven (64%) produced discernable lesions in only one rib (and one stab resulted in no lesions whatsoever). Despite minor involvement of L8, the point that struck Shanidar 3 did not forcefully incise two ribs, and by inference the depth of penetration was probably more like what we observed with stabs under low KE conditions.

Second, the injury to Shanidar 3 did not entail fracturing or infraction of the rib, did not generate radiating fractures lines nor wastage nor hinging, and does not evince crushing. Given the complete lack of associated defects, the lesion in Shanidar 3's L9 is most consistent with an injury by a weapon carrying a low amount of kinetic energy (Table 7). Given the penetration depths we observed under low KE conditions (Table 6), such a wound would certainly be sufficient to rupture the lateral parietal pleura, which in modern human males would require, on average, a wound of only 22 mm depth (Bleetman and Dyer, 2000) as well as puncturing the lung or diaphragm.

A low KE, penetrating wound to the left thorax of Shanidar 3 is still consistent with a number of scenarios, including wounding from a long-range projectile weapon (dart), knife stab, self-inflicted accidental injury, and accidental stabbing by a hunting partner. Trinkaus (1983) argued that the angle and position of the wound made it unlikely to be self-inflicted (e.g., accidentally impaling oneself on one's own spear), and that the placement and inclination of the injury was consistent with a frontal assault by a right-handed attacker, although accidental stabbing (e.g., a hunting accident) by a member of Shanidar 3's social group could not be ruled out. In agreement with Trinkaus, we also find it hard to imagine a scenario by which a Neandertal hunter would find the tip of his own spear stuck in the side of his chest, especially with the weapon oriented in a superolateral to inferomedial position (based on the downward penetrating angle suggested by the slope of the lesion). Accidental stabbing by a hunting partner remains an open possibility, especially given the presumed close-quarters and likely dangerous predatory tactics of Neandertals (Geist, 1981; Churchill, 1993; Berger and Trinkaus, 1995; Churchill et al., 1996; Churchill and Rhodes, 2006; Shea, 2006). If Shanidar 3 was impaled by a fellow hunter, it appears that the blow did not carry the full force with which Neandertals probably delivered thrusting

spears (and thus it may represent an analog to a “check-swing,” in which the hunter realized his error and tried to check the thrust before it struck his partner).

At least two morphological features of the lesion suggest that the weapon was traveling downwards into Shanidar 3’s rib cage. First, the floor of the lesion is inclined at a modest superolateral to inferomedial angle. Second, the internal widening of the lesion also suggests an oblique penetration angle. It has been experimentally shown that ballistic wounds from arrows can produce internal beveling in bone similar to that seen in gunshot wounds (see Smith et al., 2007: Fig. 3), which raises the possibility that the widening of the lesion in Shanidar 3 was the consequence of injury from a high-velocity projectile. However, the clean margins of the lesion and the lack of exostotic remodeling within the lesion indicates that the shape of the lesion represents the shape of the embedded portion of the point (in other words, if the widening was due to internal beveling, we would have expected new bone to grow into the vacant space during the formation of the callus). Given the lenticular or quadrilateral cross-sectional shape of Middle Paleolithic pointed lithics (which produces the characteristic V-shaped lesions [see Smith et al., 2007: Fig. 7]), a point that incises the margin of a rib at an oblique angle will leave a wound that increases in diameter from lateral to medial. In the case of a point traveling downwards and inwards, the edge would incise less deeply on the lateral aspect and would create a narrower lesion there, and would cut more deeply into the medial side of the rib, leaving a wider wound track (Fig. 13). Granted, we do not know the position of Shanidar 3 at the time of injury: if he were standing, the downward trajectory of the weapon would be most consistent with a knife thrust or the penetration of a dart descending along a ballistic trajectory. Either scenario implies non-accidental injury (while hunters do occasionally accidentally wound their colleagues with projectile weapons, it seems improbable that someone would launch a spear at an animal target with a fellow hunter in close proximity). It is also possible that Shanidar 3 incurred a wound from a hand-thrown spear (rather than a spearthrower-delivered dart), which might suggest injury by a member of his own social group or from conspecifics from another group. Based on design considerations seen in Middle Pleistocene wooden spears, it has been argued that humans were employing hand-thrown projectile weapons since before the Mousterian (Thieme, 1997, 1999). While considerable discussion and experimental work has focused on the question of whether these spears represent true long-range projectiles or close-range weapons (Rieder, 2001, 2003; Schmitt et al., 2003; Shea, 2009; Villa and Lenoir, 2009), most workers remain open to the possibility that by Middle Paleolithic times humans may have been throwing spears relatively short distances (10–15 m). Given lengths of 1.8–2.5 m and maximum diameters of 29–47 mm (based on the spears from Schöningen [Thieme, 1999]), Mousterian spears were likely relatively massive, on the order of about 0.75–1.25 kg. To produce a low KE stab (27.9 J, based on the mean KE of darts [Tables 1 and 2]), such massive spears would have had to have been traveling at very low velocities (on the order of 6.7–8.6 m sec^{-1}). Assuming a launch height of ca. 1.7 m, which is the estimated average height of the Shanidar Neandertal males (Trinkaus, 1983) and a target height of ca. 1.13 m (roughly two-thirds of Shanidar 3’s estimated stature), at even a 45° launch angle the maximum distance traveled by the spear would have been about 8 m. If the wounding implement was a heavy Mousterian spear in flight, it was lobbed at low speed from relatively close range (it is obviously not certain how hard a Neandertal could throw a spear, but given that modern human javelin throwers can, with a running start, achieve launch velocities of 25.5 m sec^{-1} with 0.8 kg javelins [Miller and Munro, 1983], it seems likely that a Neandertal could do better than 8.6 m sec^{-1}). A close-range throw would also involve a flatter trajectory, and would thus be less likely to create a sloping wound track in a rib. Again, assuming a heavy Mousterian spear, launches from farther away – because they require higher velocities – would, with such heavy spears, produce KE values more comparable to thrusting spears than spearthrower darts (for example, at the 16 m sec^{-1} launch velocity needed to cast a spear 25 m, 0.75–1.25 kg spears would produce KE values in the range of 96–160 J). Given these considerations, it seems unlikely that Shanidar 3 was injured with a heavy Mousterian spear operating as a missile.

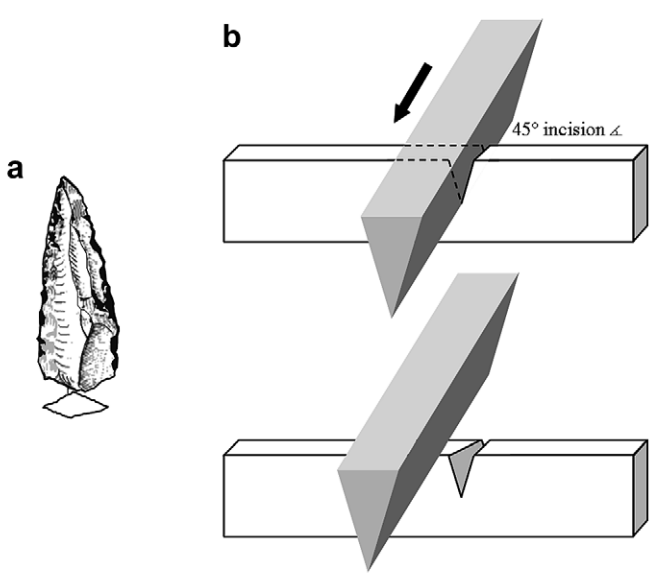

Figure 13. a) elongated Mousterian point from layer D at Shanidar Cave, showing quadrilateral cross-sectional outline (redrawn from Solecki and Solecki (1993)); b) schematic illustration showing how a lithic edge (from a point with a lenticular or quadrilaterally-shaped cross-section) can, when incising a bone margin at an angle, create a lesion that widens internally.

It is also possible that Shanidar 3 was stabbed with a knife. The kinematics and biomechanics of knife attacks have received some recent experimental attention, for the purpose of improving the effectiveness of protective garments worn by prison guards and police officers. Knife attacks can vary considerably in their kinematics (Miller and Jones, 1996), but, based on reported incidents, tend to take one of three forms: a short thrust forward, a horizontal sweep around the body, and an overhand stab (Chadwick et al., 1999). A horizontal sweep or a downward thrust from a right-handed attacker (Trinkaus, 1983) could produce the downward sloping wound trajectory seen in Shanidar 3, and the location of the wound (lateral thorax) is certainly consistent with a knife attack. The potential to damage vital organs, combined with the greater penetration potential (the tightly stretched skin over the ribs requires only half the force needed to produce blade penetration through slack skin [Horsfall et al., 1999]), makes the chest a primary target of homicidal knife attacks (and accordingly, thoracic lesions are the leading cause of death in knife attacks [Banasr et al., 2003]). However, knife attacks generally involve a relatively high kinetic energy: the US standard for the design of protective clothing is based on stabs at 210 J (see Horsfall et al., 1999). Forty-two joules is generally considered to be representative of the average knife attack (Connor et al., 1998), although experimental studies with instrumented knives report averages on the order of 36 J and 40 kg m sec^{-1} momentum (Chadwick et al., 1999), and 26–46 J, representing underarm and overarm stabs, respectively (Horsfall et al., 1999). Thus, while some stab attacks (such as short, underarm thrusts) may fall in the lower KE range, knife attacks on average

tend to carry KE comparable to thrusting spears. Not surprisingly, sharp force lesions in bone caused by knife attacks tend to be associated with the same defects observed in our high KE stabs (notably wastage, hinging, and radiating fractures [see Frayer and Bridgens, 1985; Vesterby and Poulsen, 1997]). Involvement of multiple ribs, even with a single stab, may occur with thoracic knife wounds, as may complete incision of rib bodies (Frayer and Bridgens, 1985). While we cannot definitively rule out a knife attack in the case of Shanidar 3, the apparently low KE conditions that created his wounds, along with the lack of associated defects and involvement of other ribs, argue against this scenario.

Snapping of the distal tip of a lithic point, with the detached portion remaining embedded in bone, seems equally likely under all of the above scenarios. Analyses of Mesolithic cutting arrows (Noe-Nygaard, 1974; Friis-Hansen, 1990) reveal a common pattern of lithic fracturing upon bone impact, and lithic fragments embedded in faunal remains are known from both Middle Paleolithic (Boëda et al., 1999) and Middle Stone Age (Milo, 1998) contexts. Shea (1988, 1990) and Solecki (1992) reviewed evidence that lateral snapping (mesial breakage) is a common outcome of impact between lithic points and hard objects such as bone, and documented the occurrence of this type of damage in Mousterian points from a variety of Near Eastern sites. Unfortunately, mesial breakage can result from a number of different uses of a lithic point, and also cannot differentiate projectile impact from thrusting impact. Cases of flint points embedded in ribs, with callus formation around the implement, are not infrequent in faunal remains. Good examples include an aurochs (*Bos primigenius*) skeleton with a Mesolithic point embedded in the rib (Hartz and Winge, 1906), and a left 9th rib of a red deer (*Cervus elaphus*) with substantial callus formation around an embedded Mesolithic flint (Noe-Nygaard, 1974). Noe-Nygaard (1974: Plates VI, c1, c2) provided photographs of another red deer left 9th or 10th rib with a callus that, in gross appearance, looks similar to that of Shanidar 3. In this case, a small piece of flint is retained in the wound, but there is evidence that the arrowhead glanced off the rib and only left a splinter of flint embedded. These examples suggest a fairly common occurrence of projectile induced rib trauma in faunal remains, especially in cases of small points traveling at relatively high velocity (arrow heads) that shatter upon striking a rib, and may support the suggestion that Shanidar 3 was wounded with a projectile weapon. It is also clear from these examples that animals commonly survive such penetrating wounds to the thorax.

Based on our analysis of the lesion and the experimental work presented here, we feel that the wound in Shanidar 3's left ninth rib is most consistent with injury from a light-weight, long-range projectile weapon. We offer this interpretation in full recognition of both its attendant limitations and the problematic questions it raises. Variation in the kinetic energy and momentum with which projectile and hand-held weapons are delivered, variation in the morphological characteristics of traumatic lesions caused by those weapons, and uncertainty about the position of Shanidar 3 at the moment of wounding,[4] all conspire to prevent us from reaching any unassailable conclusions about the nature of the traumatic incident. We recognize that we cannot definitively rule out accidental wounding, attack with a knife, or attack with a hand-delivered, heavy Mousterian spear: while keeping an open mind about the uncertainties inherent in this type of analysis, our point is simply that the evidence at hand is *most consistent* with injury from a light-weight, relatively high velocity, long-range projectile weapon. Given the apparent lack of projectile weaponry among the Neandertals and its origins at the hands of modern humans, such an interpretation implies interspecific violence. Uncertainty in both the dating of Shanidar 3 and of the arrival of modern humans in the Zagros undermines any consideration of interspecific competition in this case (given that the contemporaneity of the two, while possible, has not been established), as does the consideration that small lithic points, with tip cross-sectional areas (TSCA) consistent with a projectile function, were probably not abundant in lithic assemblages in the Zagros until the advent of the Upper Paleolithic many millennia after the death of Shanidar 3. As noted above, however, if modern humans arrived in northern Iraq at roughly the same time they returned to the Levant, the earliest colonizers were using Mousterian technology. Pointed lithics in the Mousterian tend to be large and to have large TSCAs, which suggests a lack of investment in projectile technology. However, Mousterian and Levallois points are variable in size, and some are relatively small: Shea (2006) reported a mean TCSA for small Mousterian points from layer D at Shanidar of 61 mm^2, not substantially different from the mean value for ethnographically- and archaeologically-known dart tips (58 ± 18 mm^2, $n = 40$). Shea attributed the small size of these points to prolonged use and resharpening rather than use as projectile armatures, but the fact remains that there existed in the late Mousterian of the Zagros points of sufficiently small size for service as projectile armatures.

Some mention should also be made of a possible weapon-inflicted lesion in a Mousterian-associated modern human from Skhul Cave, Israel. McCown and Keith (1939) described a rectangular opening through the head of the left femur and acetabulum of Skhul 9, a Levantine early modern specimen now dated to 90–120 ka (Stringer et al., 1989; Mercier et al., 1993), and on the basis of a lack of a recovered weapon armature, argued that it had been made by a wooden spear (with subsequent disintegration of the wooden tip). A second, less deep, lesion penetrates the ilium above the superoposterior margin of the acetabulum. A cast of the primary lesion (McCown and Keith, 1939: Plate XXVIII C) reveals damage by a quadrilateral (in cross-section), pointed implement (possibly the tip of a wooden spear, certainly not a hafted lithic spear point) that penetrated bone to a depth of >5 cm. A number of observations militate against McCown and Keith's conclusion. First, it is difficult to conceive that enough power could be mustered by an individual using a wooden thrusting or projectile spear to pierce entirely through the gluteal musculature, femoral head, acetabulum, and well into the pelvic basin in a single thrust. It is uncertain how much force would be required to completely penetrate the cortical and trabecular bone of the femoral head, acetabulum, and ischium, but forces on the order of 540 N are required to cause a knife to penetrate the ca. 0.5 cm thick bone of the cranial vault (parietal) (Lynnerup, 2001; Caldicott et al., 2004). Schmitt et al. (2003) observed a maximum force at strike of 3430 N in experimental work with thrusting spears (average force $= 1660 \pm 623$ N), and thus it may be possible that a wooden spear could be forcefully driven through 5 cm of bone, although this seems unlikely.

A second observation that argues against McCown and Keith's interpretation of the damage to the left hip of Skhul 9 concerns the relative orientations of the os coxa and femur. Alignment of the margins of the lesion in the femoral head and acetabulum reveal that the femur was flexed at an angle of about 90° at the moment of injury. This also happens to be the position in which these two

[4] We are grateful to the reviewer who pointed out the existence of a potentially confounding set of variables having to do with a lack of experimental control over the exact location of traumatic insult to the ribs, which when combined with variation in the local mechanical properties of the ribs (given variation in shaft cross-sectional properties, angulation of the rib body, etc.), may operate to obscure the exact relationship between the physical properties of the weapon and the nature of the traumatic lesions it produces. The aiming system we used was sufficient only to ensure that the spear point struck the designated thoracic quadrant; future studies should seek to gain better control over the exact point of impact.

bones were discovered *in situ* in the burial (compare Fig. 2 in Garrod and Bate [1937] with Fig. 28 in McCown and Keith [1939]). Based on these observations, and on the shape of the tip of the implement that produced the damage (McCown and Keith, 1939: Plate XXVIII C), we find the Skhul 9 hip wound to be highly questionable, and more likely the result of postmortem excavation damage with a pick-axe than perimortem injury from interpersonal violence.

The Shanidar 3 rib wound, on the other hand, clearly represents an antemortem injury (whatever the circumstances that produced it), and thus remains the most compelling case for the earliest example of possible human interpersonal violence involving weaponry. Along with the Neandertal from St. Césaire, Shanidar 3 contributes to the record of weapon-inflicted injuries in Neandertals near the time of their extinction in western Asia and Europe.

Conclusions

Weapon systems vary in important physical properties, such as the average velocity of the weapon and the kinetic energy and momentum it imparts to its target. Hand-deployed thrusting spears tend to be relatively heavy weapons that travel at comparatively low speeds. Because this weapon is hand-held, and because the moving parts of the operator's body contribute to the transfer of energy and momentum to the target, thrusting spears generally possess relatively high kinetic energy and momentum. Long-range weapon systems, on the other hand, usually employ low-mass projectiles operating at comparatively high speed. Despite the greater velocity of long-range projectiles, their relatively low mass normally results in low values of kinetic energy and momentum in these weapons.

The experimental work described in this paper reveals very different patterns of skeletal trauma in the ribs of pigs subjected to penetration with lithic points delivered under high versus low kinetic energy and momentum conditions. Stabs with high kinetic energy and momentum (comparable to a thrusting spear) produce massive damage around the site of impact, damage that usually involves multiple ribs. Low kinetic energy and momentum stabs (comparable to primitive long-range projectile weapons) tend to produce isolated lesions in single ribs, without associated damage to adjacent ribs.

The nature of the lesion to the left 9th rib of the Shanidar 3 Neandertal is *most consistent* with injury from a low kinetic energy, low momentum weapon. While this does not rule out accidental injury or attack by a conspecific wielding a hand-held weapon, the nature of the traumatic damage, combined with the wound track suggested by the placement and orientation of the rib lesion, is consistent with injury by a long-range projectile weapon traveling along a ballistic trajectory. Given the possible sympatry of this Neandertal with early modern humans, and given possible asymmetries in weapon technology between the two species, the case of Shanidar 3 is a good candidate for an instance of Neandertal-modern human interspecific violence.

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